Effect of the Human Eye Cornea Material Property on Measurement of the Intraocular Eye Pressure Utilizing Goldmann Applanation Tonometer

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Abstract— **A quarter 3D model of cornea-aqueous humor employing elastic anisotropic formulation in collaboration with Goldmann appalanation tonometer (GAT) action is investigated in order to examine the relation between the material property variation and the deviation from the true pressure inside the human eye utilizing finite element method. In addition to that, the effect of the corneal thickness variation has also been studied. However, the clinical experimental data show tremendous variation between true intraocular pressures (IOPTs) with those of gauged intraocular pressure (IOPGs). Numerical results establish how these parameter effect the readings. The present model has also been compared with the previous works and has been compared with some experimental data. This comparison establishes correctness of the proposed assumptions.**

Index Terms— **intraocular pressure, tonometer; corneal thickness, anisotropy, finite element method**

I. Introduction

Intraocular pressure (IOP) is defined as the fluid pressure of the aqueous humor inside the eye (see Fig. 1). In ophthalmology, tonometry is the measurement used to determine the fluid pressure inside the eye. IOP is a significant aspect in the evaluation of glaucoma patients. Most tonometers are calibrated to measure pressure in millimeters of mercury (mmHg). Intraocular pressure is mainly determined by the coupling of the production of aqueous humor and the drainage of aqueous humor mainly through the trabecular meshwork located in the anterior chamber angle. Intraocular pressure is measured with a tonometer. Intraocular pressure measurement is also influenced by corneal thickness and rigidity. [1,2]Ocular hypertension (OHT) is defined by intraocular pressure being higher than normal, in the absence of optic nerve damage or visual field loss. In general noninvasive methods are used to measure the intraocular pressure. Goldman applanation tonometer (GAT) is one of the most reliable probes used for such purpose named after Goldmann and Schmidt [3]. They explained the principle of the applanation tonometer, its calibration, and uses. They tried to establish the instrumental role of central corneal thickness but, all attempts were in vain due to the lack of validating experimental data. Ehlers [4] reported the influence of CCT and cornea radius on GAT readings. They found a significant correlation with CCT and no significant correlation with the radius of curvature of the cornea. In many subsequent clinical studies [5-7], CCT has been recognized as a significant source of inaccuracy in GAT readings; therefore, the main focus of the majority of these studies has been on correcting IOPG depending on the patient's CCT. However, it seems quite probable from a biomechanics point of view that other variables, such as cornea material properties, also have a significant influence on GAT readings. There is a little knowledge currently available on cornea material properties or their variability across the general population, nor have there been any methods developed for their measurement in vivo in individual patients. However, Zeng [8] claimed that porcine cornea is similar to human cornea. Hence, it enabled the identification of imperative aspects of the material properties. Anderson and Elshaikh[9] employed Mathematical shell analysis and nonlinear finite-element modeling in conjunction with laboratory experiments to study the behavior of the cornea under different loading states and to provide improved predictions of the mechanical response to disease and injury. They used porcine cornea in their experiment. In their comprehensive work, they reestablished the fact put forward by Orssengo [10] that an appropriate boundary condition would eliminate the need to model the whole-eye model with an average difference of 0.7%. This achievement could save tremendous time in numerical calculations indulging mere cornea. Hence, Dai [11] proposed a 3D finite element model for the cornea. Meanwhile, Kwon [14], discussed the effect of central corneal thickness in a simple 2D model. In this work, a more realistic representation of a quarter of the 3D model of the human eye cornea assuming possible material properties with the appropriate boundary conditions in collaboration with the modeled aqueous humor in contact with the standard Goldman Applanation Tonometer has been introduced. In fact, a series of GAT simulations are carried out to study the effect of the material properties. Then the imposed intraocular pressure is compared with the one perceived by the probe. In this model the cornea is assumed to exhibit anisotropic elastic stress-strain relation demonstrated.

II. Geometric Model

In this paper, it is assumed that the anterior and the posterior surfaces of the cornea obey the equation discussed

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by Liou [13] as given below;

$$r^2+(1+Q)y^2\ 2yR=0 \quad (1)$$

In the above equation, the origin of the anterior as well as the posterior surface is located at the centre of the surface itself; on the optical axis of the cornea. In this equation the y axis points inwards (opposite to the geometry) along the optical axis. Q and r are defined as the asphericity parameter and the radial distance from the optical axis. R is also the radius of curvature at the apex. It is assumed that R is 7.77mm and 6.40mm at anterior and the posterior surfaces respectively [14]. Also it is assumed that Q is -0.18 and -0.60 for the anterior and the posterior surfaces respectively [14].

III. Mathematical Formulation

This model comprises of linear elastic transverse isotropic model in which the material is assumed to be symmetric about an axis. Hence the material is isotropically in the planes normal the assumed axis. In this model the Y-axis is taken to be the axis of symmetry since it is normal to the corneal surface. Since our model is 3D, the X-axis and the Z-axis are taken to be parallel to the corneal tangency discussed by Boresi and Chong [12] given by

$$\begin{bmatrix} E_{11} & E_{12} & E_{13} & E_{14} & E_{15} & E_{16} \\ E_{21} & E_{22} & E_{23} & E_{24} & E_{25} & E_{26} \\ E_{31} & E_{32} & E_{33} & E_{34} & E_{35} & E_{36} \\ E_{41} & E_{42} & E_{43} & E_{44} & E_{45} & E_{46} \\ E_{51} & E_{52} & E_{53} & E_{54} & E_{55} & E_{56} \\ E_{61} & E_{62} & E_{63} & E_{64} & E_{65} & E_{66} \end{bmatrix} \quad (2)$$

where in this formulation, each component are given defined as;

$$E_{11}=E_{22}=E_p(1-v_{xz}^2/n)/c \quad (3a)$$

$$E_{12}=E_p(v_{xy}+v_{xz}^2/n)/c \quad (3b)$$

$$E_{13}=E_{23}=E_p(1+v_{xy})/nc \quad (3c)$$

$$E_{33}=E_p(1-v_{xy}^2)/nc \quad (3d)$$

$$E_{44}=(E_{11}-E_{12})/2 \quad (3e)$$

$$E_{55}=E_{66}=G_{xy} \quad (3f)$$

where the values of c, n, v_{xy} and G_{xy} are defined below as;

$$C=1-v_{xy}^2-2v_{xy}^2/n-2v_{xy}v_{xz}^2/n \quad (4a)$$

$$n=E_p=E_z \quad (4b)$$

$$v_{xy}=v_{xz}=v \quad (4c)$$

$$G_{xy}=E_p/[1+n(1+2v_{xy})] \quad (4c)$$

IV. Material Property

Considering the equations given in section 2.2, the instrumental inputs to the constitutive relation are two independent elastic constant; namely, E_p and the assumed value of v. Earlier kwon [14] discussed its implementation and investigation on a simplified 2D model. In this model, it has been emphasized to examine the role of different values discussed by him. In fact, there are series of experimental test to identify the material property of the human eye cornea. Fig. 3 depicts the Cauchy stress versus the logarithmic strain in a uniaxial tension test on the excised strip of cornea. In this diagram, Wollensak[16] arrived to its results via five tests. Bryant [17] investigated on nine tests while Hoeltzel [18] after three-cycle preconditioning and Zeng [19], on the basis of fitting over ten tests. Meanwhile, Bryant [20], in an in vitro inflation test, mounted each cornea on an artifial chamber and its apical displacement was measured during incremental pressure increases. Here for simplicity it is assumed that mentioned material parameters are independent but, the inflation test results appear to indicate that the greater the initial slope of the pressure–displacement curve indicating some dependency on the material parameters.

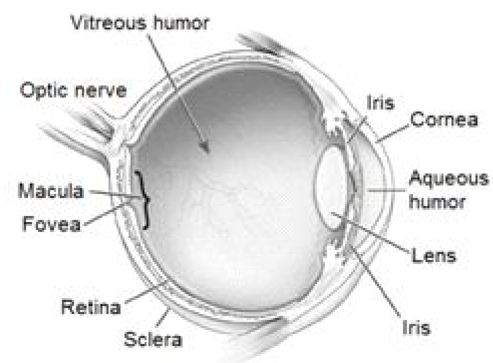

Figure 1. Anatomy of a human eye.

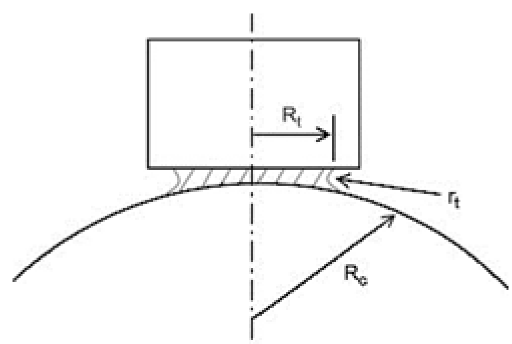

Figure 2. Tear-cornea-tonometer interface Schwarts [15]

V. Tear Inclusion Effect

Schwarts [15], in his investigation, demonstrated the effect of the pressure drop across the tear meniscus between the cornea and the edge of the applanator. He calculated the pressure drop, across the tear surface through the equation given below;

$$\Delta d=\eta(r_t^{-2}-R_t^{-2}) \quad (5)$$

where is the surface tension constant, 50dyn/cm. R_t is the radius of the fluid surface equal to 1.52mm (applanation radius), and the tear radius at the edge of the wetted area (see Fig. 2.). If $R_t^2 \sim R_c^2$, then it can conclude that $r_c\ = R_t^2/$

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($4R_c$). Here R_c is the anterior surface of the cornea assumed to be 7.77mm. Therefore;

$$\Delta d = 4.7 mmHg \quad (6)$$

Hence, hereby, in order to account for the tear meniscus effect on the IOPG reading, this value is applied to the calculations otherwise mentioned.

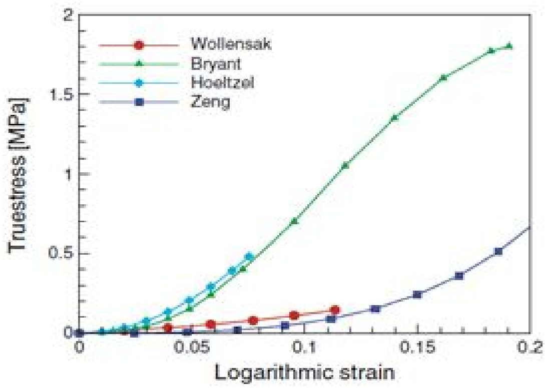

Figure 3. Cauchy stress versus the logarithmic strain from uniaxial tension tests on excised strips of cornea by Wollensak [16], Bryant [17],Hoeltzel [18], and Zeng [19]

VI. Result and Discussions

In this investigation, the quarter domain of the cornea-aqueous humor has been modeled in order to save computational time by applying appropriate boundary conditions. The assumed values for the anisotropic elastic modulus which varies from 100KPa to 450KPa can be found in literatures. A total amount of 7800 cells have been used in a quasi-static formulation employing central explicit technique. Fig. 4 shows the applanations surface mounted over the central cornea. The probe has been modeled with finer mesh compared to the rest of the model since it is an indicator of the displacement and the area being in contact synchronously. Fig. 5 illustrates the deformation of the cornea when probe is fully in contact with the cornea. The figure elicits the tension contour of the action, but the more significant thing to observe is the amount of the vertical force. In this research, the aqueous humor pressure is assumed to be held at a normal value of 15mmHg. Meanwhile, the thickness of the central cornea is assumed to be 500µm. Fig. 6 reveals that the eyes with E_p=200~225KPa do have the least error on the GAT reading. Kwon [14] established that this value is 230 KPa for central corneal thickness of 536µm through his 2D model. The interesting fact in some special cases the amount of the GAT reading might be perceived to be double the real value giving the therapist wrong intention about the patients real status. In such cases often wrong (and in some cases unnecessary) medications might be prescribed for the patient. On the other hand, when the corneal is less stiffer than 200KPa considering its anisotropic parameter, the GAT reading might be much smaller value than the real amount hence, being neglected by the therapist as a higher risked hypertension case. In most literature it is found that the human eye cornea posses a poisson's ratio varying from 0.4 to 0.5. In this research, it has been established that this variation in the value of v has less influence on the GAT reading (see Fig.7). These values have been derived from a model with E_p equal to 220KPa.

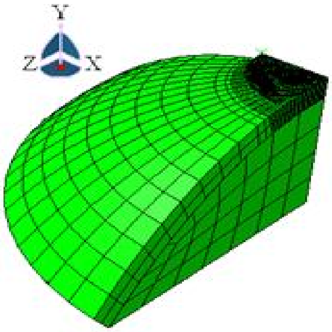

Figure 4. The Abaqus model before probe application.

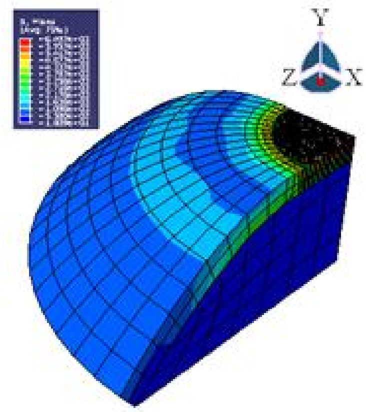

Figure 5. The model after probe application.

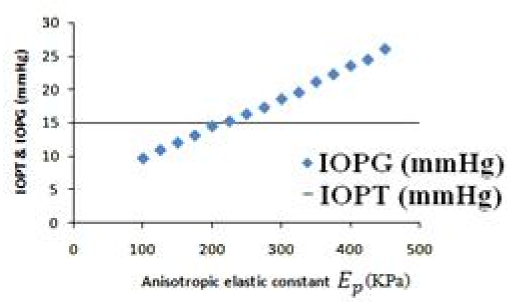

Figure 6. Elastic modulus versus IOPG on a cornea with central thickness of 500µm.

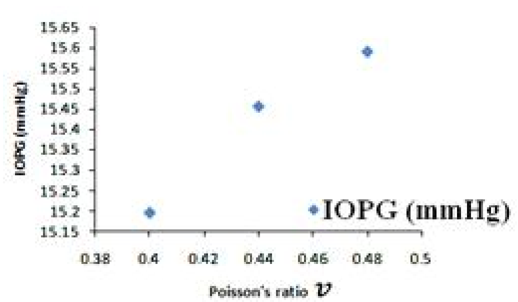

Figure 7. Poisson's ratio versus IOPG for a cornea with central thickness of 500µm.

Fig. 8 ascertains the effect of the central corneal thickness using GAT. It is evident that with the increase of the corneal thickness the measured intraocular deviates from its normal number. The other model parameters are depicted in the figure

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itself. Bhan [7] also investigated on the influence of central corneal thickness of 181 normal corneas. Meanwhile, he obtained the empirical formula demonstrated in the diagram Fig.9. The fluctuations in the established values are probably due to different values of test parameters. The value obtained here generally show good coloration with the results obtained by him.

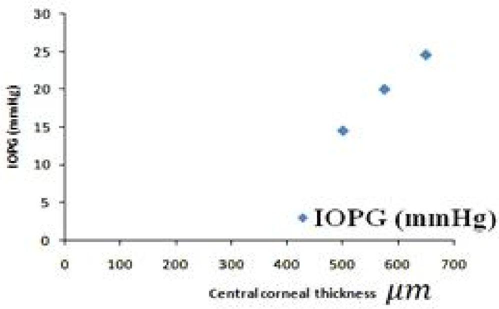

Figure 8. Central corneal thickness versus IOPG with other parameter fixed at E_p=200KPa and IOPT=15mmHg.

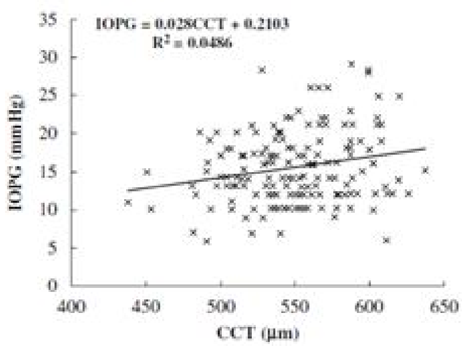

Figure 9. IOPs measured by Bhan [7] utilizing Goldmann applanation tonometer in 181 normal corneas.

Conclusion and Summary

In this investigation the physical parameters influencing the correct readings of the Goldmann Applanation Tonometer has been examined considering a quarter 3D cornea-aqueous humor model. In literatures it was established that mere modeling of cornea and aqueous will result in reliable simulation employing appropriate boundary conditions. It is assumed that all eye exhibit similar geometrical shape. The intraocular pressure of the eye has also been kept constant throughout the analysis. An anisotropic elastic model depending on only two parameters was employed. The results obtained show dependency of the influencing factor which digress the gauged intraocular pressure from the true intraocular pressure in a human eye. Consequently, as the corneal stiffness strays away from an established number (E_p=200~225KPa in this paper), the IOPG need calibration. In addition, when the thickness rambles a certain value the measured IOP is highly influenced.

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